User's Guide to CAMEX-4 PR-2 Data

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1. Introduction

The Second Generation Precipitation Radar (PR-2) is a dual-frequency, Doppler, dual-polarization radar system. PR-2 was operated on the NASA DC-8 aircraft during the Fourth Convection and Moisture Experiment (CAMEX-4).   Data were collected on all 13 CAMEX-4 flights and have been calibrated and processed. This user's guide describes the PR-2 instrument and the data collected during CAMEX-4. This version of the data is called 0.9 to indicate the preliminary nature of the data. Users should contact the PR-2 team prior to using the data. A revised version of the data (v1.0) will be delivered at a later date.
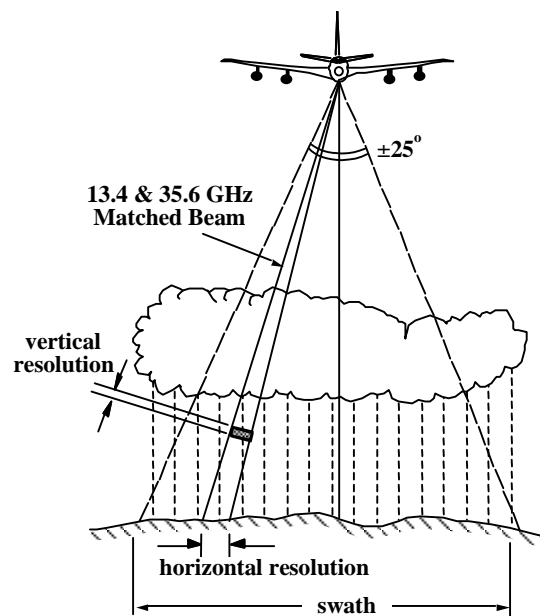
Fig. 1. PR-2 operational geometry on the NASA DC-8 aircraft.
Antenna is scanned in cross-track plane.

2. PR-2 Description

The launch of the Tropical Rainfall Measuring Mission (TRMM) satellite [1] in late 1997 has made a great stride towards understanding the global structure of precipitation. The Precipitation Radar (PR) aboard the satellite is the first-ever spaceborne radar dedicated to three-dimensional, global precipitation measurements over the tropics and the subtropics.

Because of the TRMM success, a follow-on mission, called the Global Precipitation Mission (GPM), is currently being planned to extend the TRMM's instrument capability in such a way to fully address the key science questions from microphysical to climatic time scale. The baseline GPM configuration includes a high-resolution, wide-swath

scanning, dual-frequency radar. A second generation dual-frequency precipitation radar (PR-2), which could be used for GPM or follow-ons to GPM has been designed [2]. This system includes digital, real-time pulse compression, extremely compact RF electronics, and a large deployable dual-frequency cylindrical parabolic antenna subsystem. The antenna is fed by a linear active array for electronic beam scanning.

To demonstrate many of the key PR-2 technologies and designs, an airborne version of PR-2 has been developed. The airborne PR-2 system includes a real-time pulse compression processor, a fully-functional control and timing unit, and a very compact LO/IF module, all of which could be used in spaceborne applications. The cylindrical reflector antenna and linear feed array for the spaceborne PR-2 have been replaced by traveling wave tube amplifiers (TWTAs), front-end electronics, and an offset parabolic reflector antenna with mechanical scanning. The airborne PR-2 operational geometry is shown in Fig. 1; it looks downward and scans its beam across-track, with each scan beginning at 25 degrees to the left of nadir and ending at 25 degrees to the right. It uses the same scanning antenna reflector as that used for the Airborne Rain Mapping Radar (ARMAR) [3]; it consists of a 0.4 m offset reflector antenna with a mechanically scanned flat plate. For PR-2 the 13.8-GHz antenna feed has been replaced by a dual-frequency feed (13.4 and 35.6 GHz) and the aperture at 35.6 GHz is under-illuminated to provide matched beams at the two frequencies. This choice results in poor Doppler accuracy at Ka-band, but is needed for rain retrieval. Table 1 shows the parameters for the airborne PR-2.

The RF circuitry can be divided into two categories: circuits operating at frequencies of less than 1.5 GHz and circuits operating at frequencies above 1.5 GHz. The lower frequency (below 1.5 GHz) circuitry is all contained in a single unit, the local oscillator / intermediate frequency (LO/IF) module. This unit converts transmit chirp signals from 15 MHz up to 1405 MHz and downconverts received IF signals from 1405 MHz to 5 MHz. The unit contains both upconversion channels and all four receive channels and fits into the equivalent of a double wide 6U-VME card.

The RF front-end electronics are unique to the airborne PR-2 design and consist of five units: one local oscillator / up converter (LO/U) unit, two TWTAs and two waveguide front end (WGFE) units. In the DC-8 installation, the two TWTAs are stacked vertically in a standard rack with the LO/U in between them and the two WGFEs are mounted on top of the antenna pressure box, near the antenna feed. A calibration loop is included for each channel. This feeds some of the transmit power to the receiver, allowing in-flight variations of the transmit power and receiver gain to be monitored and removed from the data.

 The digital electronics consists of a control and timing unit (CTU), an arbitrary waveform generator (AWG), and a data processor. The CTU generates the pulse timing and all other timing signals. It also provides control signals to RF. The AWG is loaded with a digital version of the linear FM chirp that is to be transmitted. The data processor is based on FPGA technology. It performs pulse compression and averaging in real-time. Unlike ARMAR, which used a frequency domain pulse compression algorithm in post-processing, the pulse compression scheme in PR-2 is based on real-time filtering in the

time domain. The 4 MHz bandwidth received signals are sampled at 20 MHz, then digitally downconverted to complex samples, resulting in I and Q samples at 5 MHz rate. The data processor also includes pulse-pair Doppler processing. The output of the processor is the lag-0 (power) and lag-1 (complex Doppler data) for the co- and cross-polarized channels at each frequency. A VME-based workstation runs the radar, including ingesting and saving the processed data. Following calibration on the ground, the PR-2 data are stored in a HDF format similar to that from the TRMM PR.

Table 1. Airborne PR-2 Parameters

Frequency	13.4 GHz	35.6 GHz
Polarization	HH, HV	HH, HV
Antenna diameter	0.4 m	0.14 m
Beamwidth	3.8 deg	4.8 deg
Antenna gain	34 dBi	33 dBi
Antenna sidelobe	-30 dB	-30 dB
Polarization isolation	-25 dB	-25 dB
Peak power	200 W	100 W
Bandwidth	4 MHz	4 MHz
Pulse width	10-40 μs	10-40 μs
PRF	5 kHz	5 kHz
Vertical resolution	37 m	37 m
Horizontal resolution	800 m	800 m
Ground Swath	10 km	10 km
Noise-equiv. Ze (10 km range)	5 dBZ	5 dBZ
Doppler precision	0.4 m/s	>1 m/s

3. PR-2 Data Collection in CAMEX-4

PR-2 operated on all 13 flights of the DC-8 during CAMEX-4. Parameters under operator control were generally set to the same values throughout the experiment, with the exception of the receive window attenuation, which must be varied with surface brightness. The pulse length was always set to 10 microseconds and the PRF to 5000 Hz. The number of pulses averaged in real-time was 250. This is equivalent to about 60 independent pulses. The elevation angle of the antenna (i.e., along-track angle) was set during flight to maintain a near zero Doppler from the surface, minimizing platform motion contamination to the measured Doppler from precipitation. The platform motion was estimated from the surface and subtracted during ground processing. The azimuth scan limits were about +/- 23 degrees.

The commercial off-the-shelf Ka-band TWTA had a problem with faulting while operating on the DC-8. The problem was much less frequent in ground-based operation, including on the aircraft. This problem precluded acquisition of a full set of Ka-band data. However, several significant segments were acquired. The Ku-band channel

acquired data throughout the experiment. Table 2 below shows the data collected in CAMEX-4.

Table 2. PR-2 Operation on CAMEX-4 DC-8 Flights

Flight No	Date	Comments
010406	8/18/01	Ku-band only, some isolated convective cells
010407	8/20/01	Ku-band only, TS Chantal
010408	8/25/01	Clear air, first Ka band return from ocean surface
010409	9/03/01	Ka sporadic but obtained first dual-freq returns from rain; Ka for several minutes around 1638 and 1705 UTC
010410	9/06/01	Ku-band, some Ka over rain (1704-1712, 1749-1800, 1820, 1840); problem with antenna scanning
010411	9/07/01	Ku-band, good Ka over rain (1759-1810)
010412	9/09/01	Ku-band over stratiform rain; Ka 1826-1831; problem with antenna scanning
010413	9/10/01	Clear air flight around Hurricane Erin (little or no precip)
010414	9/15/01	Ku and some Ka (2240-2250) data in TS Gabrielle
010415	9/19/01	Mostly Ku-band in isolated cells; Ka 1729-1731, 1920
010416	9/22/01	Ku and some good Ka (2146-2155) data in TS Humberto
010417	9/23/01	Ku and some Ka (near 0020 UTC) in Hurricane Humberto
010418	9/24/01	Ku with Ka from 0011 to 0028, in Hurricane Humberto

4. Data Format

The raw PR-2 data are saved in a PR-2 unique format. These data are run through a processor which calibrates the data to reflectivity Z, LDR, and velocity. A second processor then uses these data and the DC-8 navigation data to create a geolocated Level 1 B product. This product is saved in a Hierarchical Data Format (HDF) format similar to the TRMM Precipitation Radar. Table 3 shows the objects within the HDF format.

Table 3. PR-2 HDF Objects

- File header, 72 bytes
- ScanTime , 4 bytes, nscan
- DC8_Lat, 4 byte, nscan
- DC8_Lon, 4byte, nscan
- DC8_Alt , 4 bytes, nscan
- Ray sequence number, 2 bytes, nscan x nray
- Range to 1st bin, 4 bytes, nscan x nray
- Surface Bin Number , 4 bytes, nscan x nray
- Number pulses averaged, 4 byte, nscan x nray x 4
- Look vector, 8 bytes, nscan x nray x 3
- Radar surface Doppler, 4 byte, nscan x nray
- Surface Doppler from DC8 Nav., 4 bytes, nscan x nray
- Zhh at Ku-band, 2 bytes, nscan x nray x nbins
- Doppler at Ku-band , 2 bytes, nscan x nray x nbins
- LDR at Ku-band , 2 bytes, nscan x nray x nbins
- Zhh at Ka-band (if available), 2 bytes, nscan x nray x nbins

Within Table 3, nscan is the number of scans in a file, nray is the number of rays, or beams, within a scan, and nbin is the number of bins within a ray. The first five items in Table 3 are stored as Vdata; the remaining items are Scientific Data Sets (SDSs). The last four items in Table 3 are the PR-2 reflectivity, Doppler, and Linear Depolarization Ratio (LDR) data. The data also include a look vector which specifies the 3 components of the antenna relative to a global coordinate system with x being the aircraft ground track and z being nadir. The predicted and observed surface Dopplers are also provided. The number of pulses averaged is the total number of samples that were used for the radar measurements. The sequence number should be contiguous through a file. The scan time is seconds since 1 January 2001. The DC-8 lat and lon are floating point values, as reported in the DC-8 navigation files. The altitude is the DC-8 radar altitude, converted to meters. The file header contains information about the PR-2 data. These are parameters that are constant over the entire file. Table 4 shows the file header. A

sample IDL routine is available for reading PR-2 HDF data. FORTRAN or C code can also be constructed using the HDF libraries available from NCSA.

Table 4: File header

	Name	Format	Description
1	PRF	4-byte integer	Pulse repetition frequency in Hz
2	Pulse Length	4-byte integer	Radar pulse length in 1 us units
3	Antenna Left	4-byte integer	Antenna scan left-limit in deg.
4	Antenna Right	4-byte integer	Antenna scan right-limit in deg.
5	Scan Duration	4-byte integer	Scan time for antenna in second * 100
6	Return Duration	4-byte integer	Antenna retrace time in second * 100
7	Ncycle	4-byte integer	Number of pulse averaged by Wildstar board
8	AZ Average	4-byte integer	Number of blocks averaged in a beam or ray
9	Range average	4-byte integer	Number of 30m range cells averaged in a bin
10	Scan average	4-byte integer	Number of scans averaged
11	Number of Bins	4-byte integer	Number of range bins in the ray
12	Number of Beams	4-byte integer	Number of rays in each scan
13	Range Bin Size	4-byte integer	The vertical resolution of range bin
14	Z scale factor	4-byte integer	Factor multiplying reflectivity
15	V scale factor	4-byte integer	Factor multiplying Doppler
16	Valid Ka scan begin	4-byte integer	Scan number where the valid Ka data begin
17	Valid Ka scan end	4-byte integer	Scan number where the valid Ka data end
18	CalVersion	4-byte integer	Version number of the calibration table

In the course of processing browse images are also created. These are saved in JPEG format. They generally show the nadir beam of PR-2 data versus along-track time, providing a nadir slice from the data. On occasions other beams rather than nadir were chosen on the basis of interesting features in the data. The beam number is labeled on the image, with beam 11 being near nadir, beam 0 being leftmost beam, and beam 21 being the rightmost. Fig. 2 shows an example.
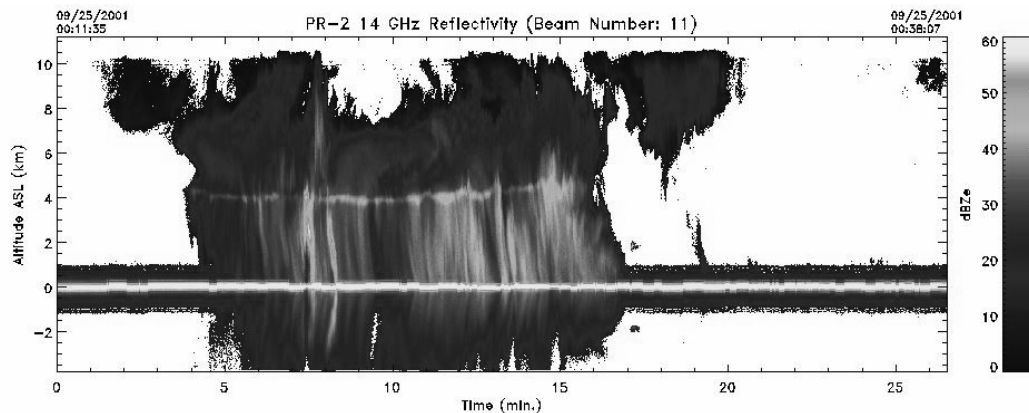

Figure 2. Example browse image showing nadir view. Bright horizontal line is surface return. Vertical axis is altitude and horizontal axis is time.

5. CAMEX-4 Data Quality

The PR-2 data quality has been assessed by examining a number of engineering parameters related to the radar's stability and calibration. Fig. 3 shows the observed minimum detectable reflectivity Z for PR-2 at both frequencies. This was derived from clear-air observations. The values for both Ku-band and Ka-band are below 5 dBZ at 10 km range from the radar. The surface return, along with pulse compression sidelobes can be seen at approximately 12 km range. The pulse compression sidelobes, rather than thermal noise, limit the performance near the surface. Achieving such low pulse compression sidelobes required careful design of the transmit waveform and control of gain and phase errors.

Also of concern is the calibration of the radar. Calibration can be verified using observations of the ocean surface. This technique has been used previously with ARMAR [3], since the ocean backscatter near nadir is well known, especially near 10 degrees incidence, where sensitivity to wind speed is a minimum. Ocean backscatter at Ka-band is much less well characterized, although models show similar behavior to Ku-band. At Ka-band the reflectivity in very light rain should be nearly identical to that at Ku-band, since Rayleigh scattering should apply at both frequencies. Observations of the ocean surface with PR-2 show a cross section near 7 dB, which is close to previous measurements. The Ka-band data have reflectivities within about 1 dB of the Ku-band reflectivities in light rain. Ocean backscatter observations from PR-2 are shown in Fig 4. Surface Doppler measurements can be compared with Doppler calculated from the DC-8 navigation parameters and the PR-2 antenna pointing. Fig. 5 shows such a comparison, indicating the bias between the observed and calculated Doppler is very small.
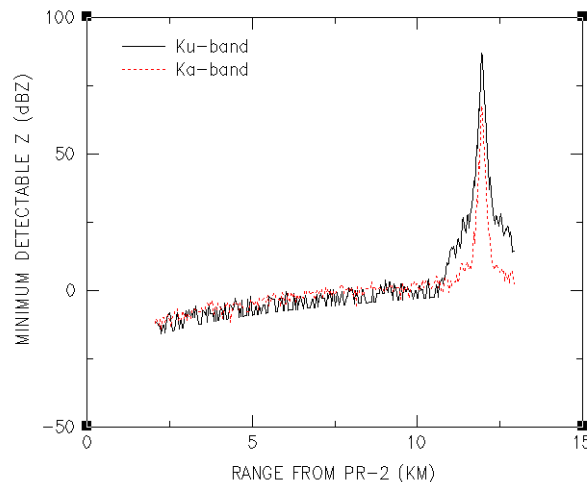

Fig. 3. Observed minimum detectable reflectivity for PR-2 as a function of range. Surface return and pulse compression sidelobes are visible at around 12 km range.
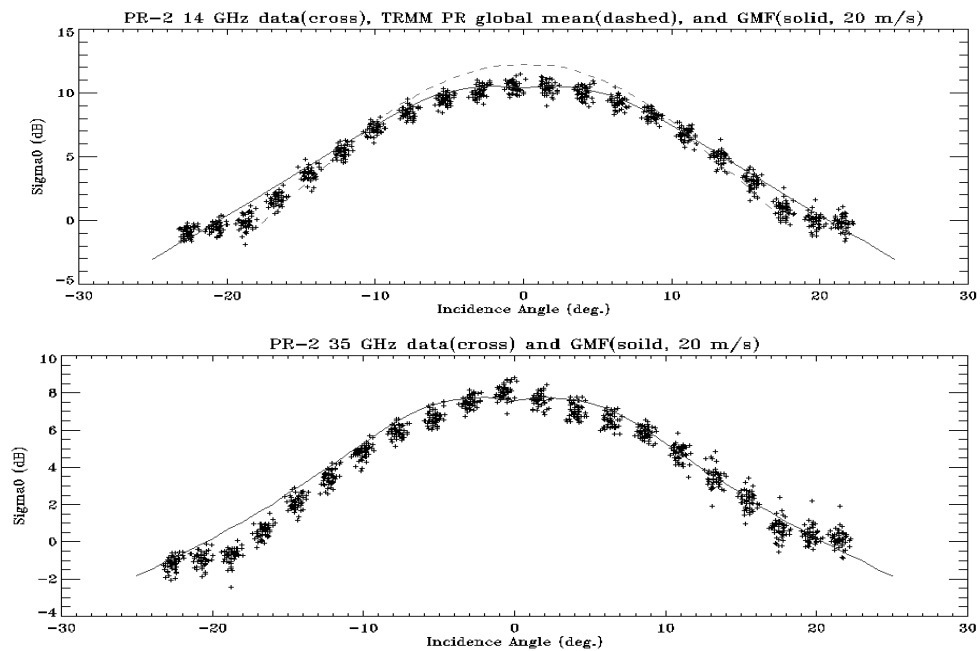
PR-2 14 GHz data(cross), TRMM PR global mean(dashed), and GMF(solid, 20 m/s)

PR-2 35 GHz data(cross) and GMF(soild, 20 m/s)

Figure 4. PR-2 observations of ocean backscatter versus incidence angle.

Mean Difference = −0.05 m/s
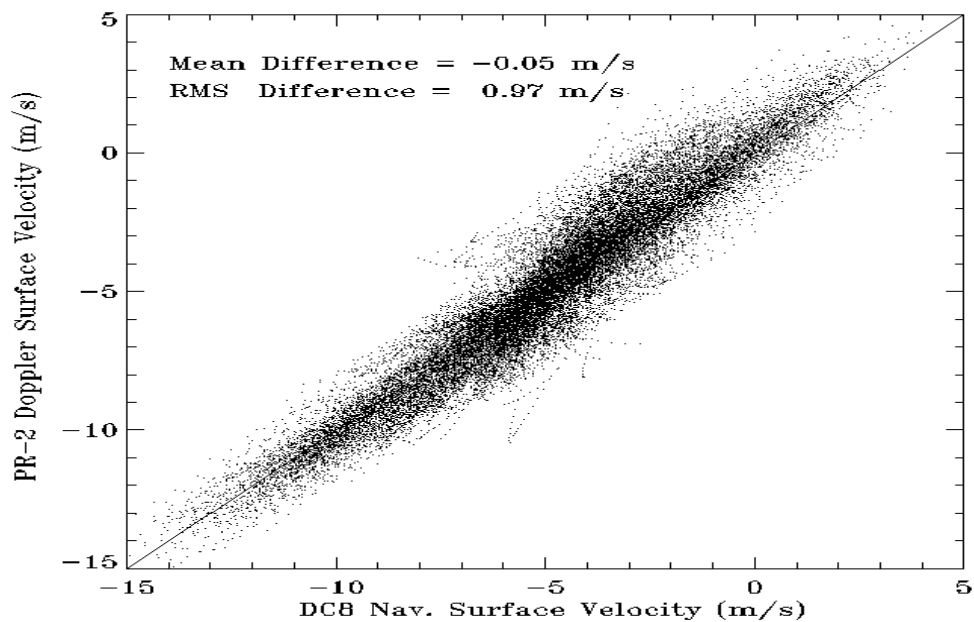RMS Difference = 0.97 m/s

Figure 5. Comparison of observed and predicted Doppler from the ocean surface.

6. Known Problems

This section lists all known problems with the PR-2 v0.9 data. Some of these problems are caused by problems in the raw data, while others are processing problems.

- Ka-band TWTA had repeated faults, allowing limited data collection
- 9/6 and 9/9 flights had "stuck" antenna scanner; all data were acquired with antenna pointing at 25 degrees to left of nadir
- LDR requires inter-channel calibration; still has moderate uncertainty at this point; especially true for Ka-band LDR, so only Ku-band LDR is in Level 1 B product
- On a number of cases the overall Ku-band calibration appears wrong, probably because of a processing or display bug; this likely only affects the browse images
- During flight 010412 on 9/9, Doppler data is unusual, probably due to error in motion correction
- Artificially high LDR can be seen at rain boundaries due to low signal to noise ratio in these areas
- Antenna sidelobes show up as artifacts in data in some cases, e.g. 9/6 at 1741
- Noise removal occasionally leaves noise strip (horizontal line at top of image or below surface) e.g., 9/3 at 1540

7. Contact Information

This data should be considered preliminary, and users should contact the PR-2 team regarding it's use, especially before publication or public presentation.

Contact information:

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PR-2 Data Processing: Dr. Li Li, li@chasm.jpl.nasa.gov, (818)354-8349

8. References

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[3] S. L. Durden, E. Im, F. K. Li, W. Ricketts, A. Tanner, and W. Wilson, ``ARMAR: An airborne rain mapping radar," *J. Atmos. Oceanic Technol*., vol. 11, no. 3, pp. 727-737, 1994.